

## **Application of Earth Sciences Products for use in Next Generation Numerical Aerosol Prediction Models**

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### **LONG-TERM GOALS**

In this project, we enhance Navy aerosol prediction systems characterization and prediction of clear sky radiation fields through harvesting a number of existing basic research programs funded by Navy and other government agencies (NASA, NOAA, DOE, etc.). By combining prognostic aerosol and meteorological fields from the NRL Aerosol Analysis and Prediction System (NAAPS) and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS<sup>®1</sup>) with near real time satellite surface and aerosol products through data assimilation and fusion methods, angular clear-sky radiance fields and diabatic heating rates can be generated and predicted. The improvements to the NAAPS model advance a number of US Navy Applied Science needs in the areas of improved Electro-Optical (EO) propagation prediction and aerosol/meteorology interaction. Further development of the Navy's atmospheric constituent data assimilation system depends on our focused efforts, including the utilization of a number of satellite-based products. The evaluation and characterization of relevant satellite products, including passive aerosol retrievals, lidar profiles, and other relevant cloud and precipitation products, does require substantial effort, but will feed into a system for the calculation and improvement of atmospheric radiance fields from Navy meteorological data feeds. Work will also enable quasi-operational computations of aerosol impacts on atmospheric diabatic heating rates and surface fluxes, as well as provide a significant upgrade to the Navy's aerosol data assimilation system through the inclusion of a number of additional satellite sensors. Lastly our efforts will significantly improve source and sink functions for Navy or other outside aerosol models, as well as prepare for expected data gaps in the early 2010's.

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## OBJECTIVES

Scientific objectives of this project over its lifecycle are tightly aligned with the long-term goals listed above, and can be broken down into the following categories by relative project order a) model data assimilation and initialization; b) source functions; c) radiative transfer; d) synthesis and scale independent integration. In this second year of the project, focus has surrounded the transition of data assimilation and its use for improving source functions. Specific objectives and status are as follows:

- Develop quality-assurance and quality-control procedures for over-land MODIS aerosol product and expand assimilation to all traditional dark-target surfaces. This development includes the evaluation of the current state of satellite aerosol measurements over land relative to the accuracy requirements of the Navy Aerosol Analysis and Prediction System. This work is tightly integrated with the over-water data assimilation development and long-term simulation work on a parallel ONR grant to Prof. Jianglong Zhang at the University of North Dakota (UND). Status: methodology defined and 2 years of test data generated. Paper nearly submitted.
- Initiate a program to develop error matrices and spread functions for the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data to use in refining aerosol vertical information. Status: NAAPS specific CALIPSO product has been created and tested in a 3-D variational analysis scheme. This work has resulted in one submitted publication.
- Based on the NAAPS analysis and assimilated satellite data, improve the smoke aerosol source descriptions and model used operationally by the Navy. Status: Two year re-analysis was performed and regional corrections to the source function have been made. Further, we completed our preliminary investigation of the impact of using a satellite-based precipitation scheme. This work resulted in two publications.
- Begin development of unified cross-platform analysis and radiation tools for the consistent use of NAAPS, NOGAPS, and COAMPS data. This includes the in-house implementation of advancements in the aerosol data assimilation system developed by Prof. Zhang at UND. Status: We have worked with Fu and Liu and SBDART schemes. In this year, a final decision as to which method will be used will be made.

## APPROACH

Work performed in FY09 focused on the finalization of appropriate error matrices for the satellite products to be assimilated, including MODIS over-land data and CALIPSO. We also investigated the use of other relevant satellite products such as high-resolution precipitation products.

High-precision aerosol measurements from the global AERONET monitoring network, coupled with land surface products for albedo and snow were used to perform a detailed evaluation of the MODIS version 5 aerosol optical depth (AOD) retrieval over land areas. After identifying and quantifying uncertainties in retrieved AOD, empirical corrections and data screening methods were finalized for use in operational and climatology based model runs. A final quality-assurance system for MODIS AOD observations generates an aggregated observation field with well-defined uncertainty for use in data assimilation applications.

For CALIPSO, a similar process was performed. However, the lack of substantive vertical information to validate lidar data makes the process much more complex. In response, we are working closely with the CALIPSO project team at NASA Langley. We are combining Navy and NASA field data along with representative CALIPSO data to develop a suitable calibration/validation data set. In order to ensure consistency with the model, a system which utilizes NAAPS AOD fields to help constrain the lidar ratio in the lidar extinction retrieval has been derived.

For other data sources, once a suitable product is available, it can be assimilated into the model. An aerosol optical depth data assimilation system has been developed at NRL that incorporates aerosol optical depth retrievals into the NRL Atmospheric Variation Data Assimilation System (NAVDAS).

As components of the satellite products/assimilation system are completed, we have begun the feedback process on improving source functions. Since the assimilation process requires a reasonable first guess by the model, several iterations between model analysis and observations over large time series are required to optimize the system. Further, because aerosol production must be balanced with sinks, evaluation of the model sink terms is required. Lastly, to improve model performance, additional species are required; particularly non-biomass black and organic carbon. As a first step, a suitable first-guess emissions inventory needs to be generated.

Finally, we wish to develop data assimilation, radiation, and source-function systems that can adapt to future improvements to the core model (including resolution) as well as be applicable to the mesoscale (e.g., COAMPS). Hence, consistent databases and software need to be available. Processing code and algorithms developed by partners (such as Prof. Zhang) also need to be integrated into the new experimental framework for long time-period test simulations.

## **WORK COMPLETED**

Over FY09, focus has been on the incorporation of satellite products into the NAAPS model. Areas of work can be categorized under:

- a) Aerosol optical depth product characterization: We completed our evaluation of the MODIS over land aerosol product and developed a level 3 data protocol for data assimilation purposes.
- b) Lidar product development: Based on a combination of NAAPS and CALIPSO data, a level 3 lidar product has been generated for use in 3D variational data assimilation systems such as NAVDAS.
- c) 2 year re-analysis: To fine tune the NAAPS smoke emissions algorithm, a two year reanalysis has been completed in both natural and data assimilation modes.
- d) Inclusion of satellite-based tropical precipitation products in aerosol model reanalyses has been performed.

## **RESULTS**

This project encompasses a number of sub-projects. Key results are as follows:

*Collection 5 over-land data-quality study:* We identified two key sources of error in the retrieved optical depths, one associated with errors in the aerosol properties specified in the retrieval, and another associated with incorrect retrieval of surface reflectance. Cloud screening bias does not appear to be significant. We used a regional slope correction to attempt to address the microphysical errors, and a linear regression against MODIS albedo data to correct the boundary condition errors. We developed and tested filters to reduce snow contamination, poorly behaved surfaces, and other problems. With a combination of filtering, correction, and aggregation to a 1-degree grid, we were able to improve the fraction of retrievals with optical depths within  $0.05 \pm 20\%$  of AERONET from 65% to 75%. An example of raw and filtered data is presented in Figure 1. We also substantially improved the correlation between MODIS and AERONET. With the errors minimized and quantified, we have produced a data set suitable for use in a data assimilation system. However, significant regional variability in optical depth retrieval errors remains, and we present suggestions for additional improvements.

*CALIPSO data assimilation:* A method was generated for constructing one-degree along-track and cloud-free signal composite averages that is consistent with Navy Aerosol Analysis and Prediction System (NAAPS) model gridding, using CALIOP Level 1B attenuated backscatter and Level 2 cloud boundary-height products. Optimal vertical resolutions and relative signal uncertainties for the composite signal averages were generated for both day and nighttime measurement scenarios, typically 3 times larger than the standard level 2 product. To help speciate dust, depolarization profiles are also used for the  $0.532 \mu\text{m}$  channel as well as attenuated color ratio profiles using  $0.532$  and  $1.064 \mu\text{m}$  attenuated backscatter measurements. Constrained by NAAPS model aerosol optical depths, attenuated backscatter profiles are now inverted to solve for extinction and backscatter coefficients, their ratio, and extinction coefficient profiles. Using this method, a 3-month data set has been generated over the subtropical Atlantic basin for testing in a 3D variational data assimilation system.

*Smoke source function:* Through a two-year reanalysis, we examined the impact of satellite data assimilation on biomass burning simulations in NAAPS. An example of natural and assimilated runs for the globe is presented in Figure 3. We found that transport simulations can be vastly improved through the use of MODIS optical-depth data assimilation; on average halving the variance between model and ground observation in regional or greater scale plumes. This said, proper characterization and error analysis of the satellite data is imperative. Assimilation of over-land MODIS AOD clearly increases correlations but some systematic bias persists. But, even with data assimilation, the chain between emissions and AOD is not well understood. It appears that emissions linearly correlate with AOD in major burning regions of the globe. Since the uncertainty in mass-extinction efficiency and hygroscopicity of smoke are small relative to emissions, comparison of AOD to emissions is not an unreasonable method to tune emissions estimates. But we can foresee a number of further uncertainties and ultimately we believe we can estimate true emissions within a factor of 2.

*Satellite-based precipitation:* By substituting precipitation from the Navy Operational Global Atmospheric Prediction System (NOGAPS) for a multi-satellite high-resolution precipitation dataset, we demonstrate the impact of modeled versus satellite-derived precipitation on aerosol optical depth (AOD) in the Navy Aerosol Analysis and Prediction System (NAAPS). The model and satellite-derived precipitation are shown to have similar precipitation amounts, but the precipitation area from the model is about twice that in the satellite data. Figure 4 shows the smoke AOD (at  $550 \text{ nm}$ ) resulting from the NRL-blend precipitation in the tropics on the left, and the ratio of smoke AOD from the NRL-blend run to that from the NOGAPS precipitation run on the right for 4 burning seasons. It shows that the

difference in precipitation and scavenging results in an increase in mid-visible AOD of about 20-200% in parts of Southeast Asia and South America during the burning seasons (or 0.1-0.2 in AOD). It indicates that the light rain over large areas in the NOGAPS meteorological model removes significantly more aerosol particles than the more realistic heavy rain in small areas found in the NRL-Blend satellite precipitation product, even though the total amount of precipitation is nearly the same in the two schemes.

## IMPACT/APPLICATIONS

The AOD datasets we have produced will allow us to directly test the forecast impact of different choices balancing aggressive data filtering with avoiding unnecessary reduction in data volume and coverage. Once the tradeoffs have been quantified, we can begin to incorporate over-land AOD observations in the NAVDAS-AOD system, thereby improving forecast skill over both land and ocean. Once fully implemented, it will be considerably easier to add additional sensors and sustain long-term support of the system. Further, with the substantially improved model efficacy data assimilation provides, it will be possible to predict higher level radiation fields and EO propagation in both the global, and eventually mesoscale models.

## TRANSITIONS

Code for optical depth data assimilation and NAVDAS-AOD has been delivered to FNMOC for implementation.

## RELATED PROJECTS

This project is tightly coupled to a number of ONR 32 programs, particularly Professor Jianglong Zhang at the University of North Dakota. Our primary transition partner is Douglas Westphal, who is principal investigator on the Large-Scale Aerosol Model Development (PI: Doug Westphal). New data-processing and visualization systems are being adapted for aerosol research through the COAMPS-On Scene (COAMPS-OS<sup>®</sup>)<sup>2</sup> IVPS charts program (PI: John Cook). We have also begun working with Jim Hansen on his ONR -funded project for the use of ensemble data assimilation in the prediction of atmospheric constituents.

## PUBLICATIONS

Eck, T. F., B. N. Holben, **J. S. Reid**, et al., 2009: Optical properties of boreal region biomass burning aerosols in central Alaska and seasonal variation of aerosol optical depth at an Arctic coastal site, *J. Geophys. Res.*, **114**, D11201, doi:10.1029/2008JD010870. [published, refereed]

Hansell, R. A., K.N. Liou, S.C. Ou, S.C. Tsay, Q. Ji, and **J. S. Reid**, 2008: Remote sensing of mineral dust aerosol using AERI during the UAE<sup>2</sup> 1. A modeling and sensitivity study, *J. Geophys. Res.*, **113**, D18202, doi:10.1029/2008JD010246. [published, refereed]

**Hyer, E. J.**, and **J. S. Reid**, 2009: Baseline uncertainties in biomass burning emission models resulting from spatial error in satellite active fire location data, *Geophys. Res. Lett.*, **36**, L05802, doi:10.1029/2008GL036767. [published, refereed]

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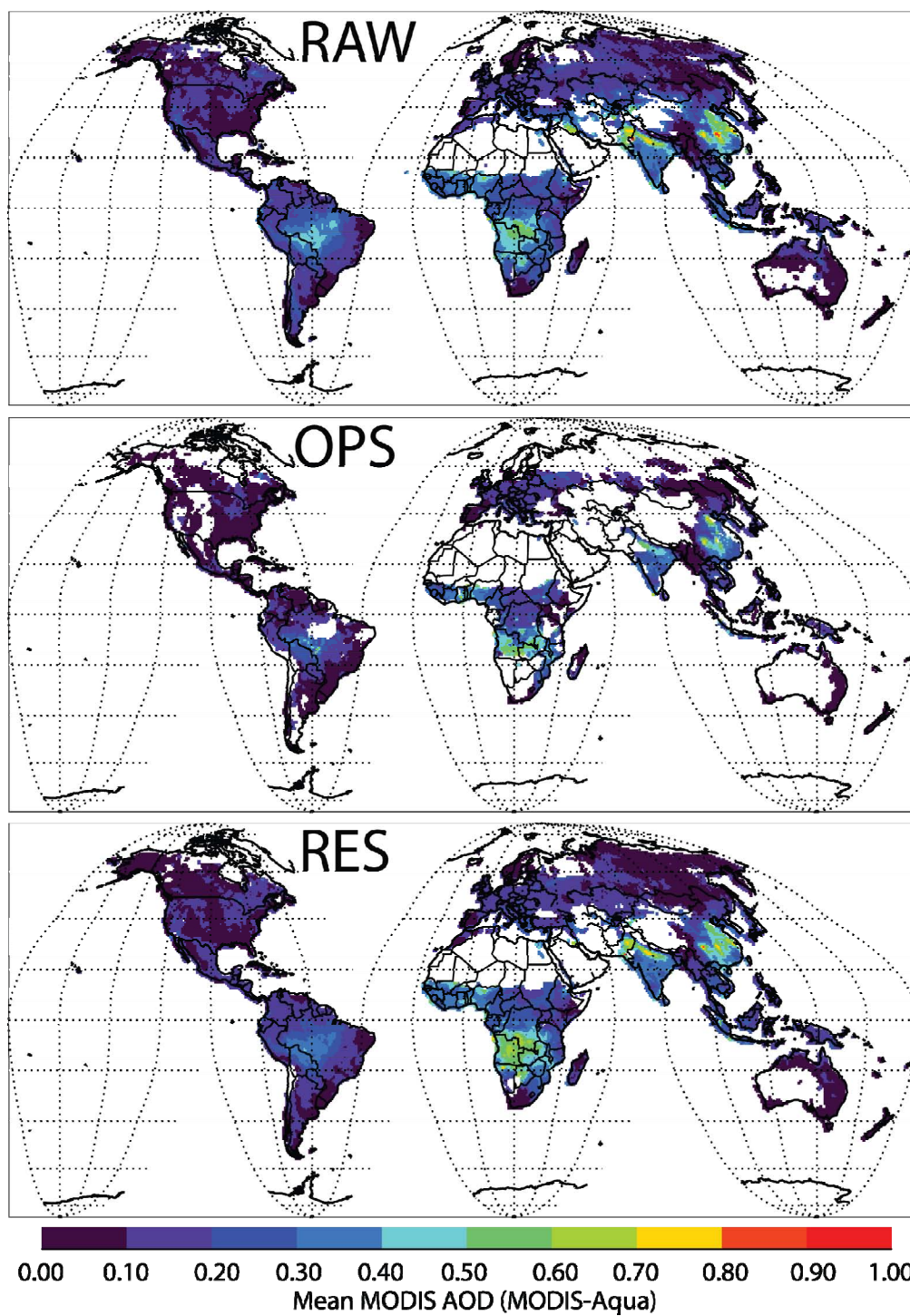
<sup>2</sup> COAMPS-OS<sup>®</sup> is a registered trademark of the Naval Research Laboratory.

Wang, J., S. Van den Heever, and **J.S. Reid**, 2009: A conceptual model for the linkage between Central American biomass burning aerosols and severe weather over the south central United States, *Environ. Res. Lett.*, doi:10.1088/1748-9326/4/1/015003, 015003 4. [published, refereed]

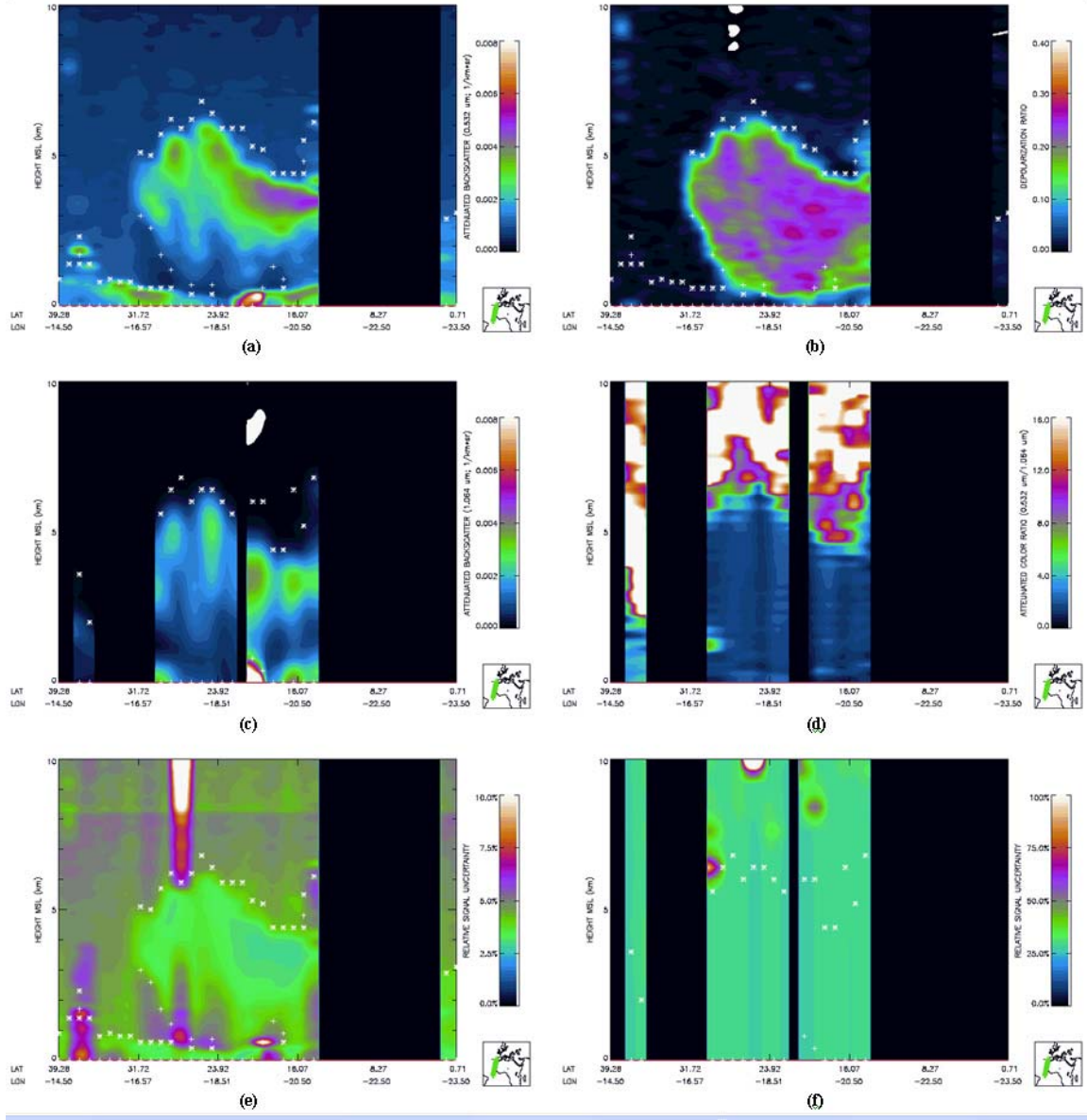
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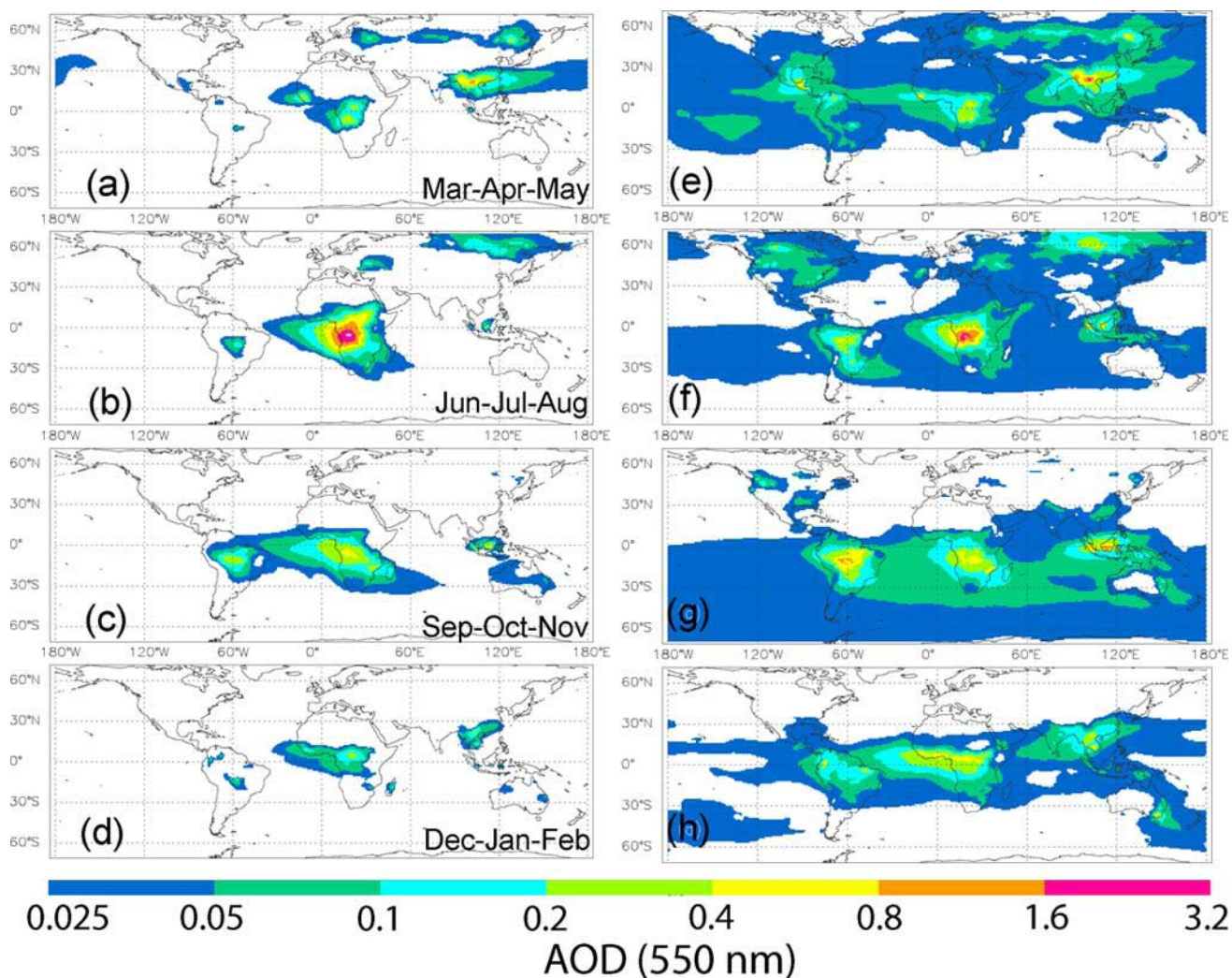




**Figure 1. Mean MODIS-Aqua AOD for September-October-November 2008 for 1-degree grid boxes using RAW, Operational (OPS) and Research (RES) filtering and correction scenarios (top to bottom).**

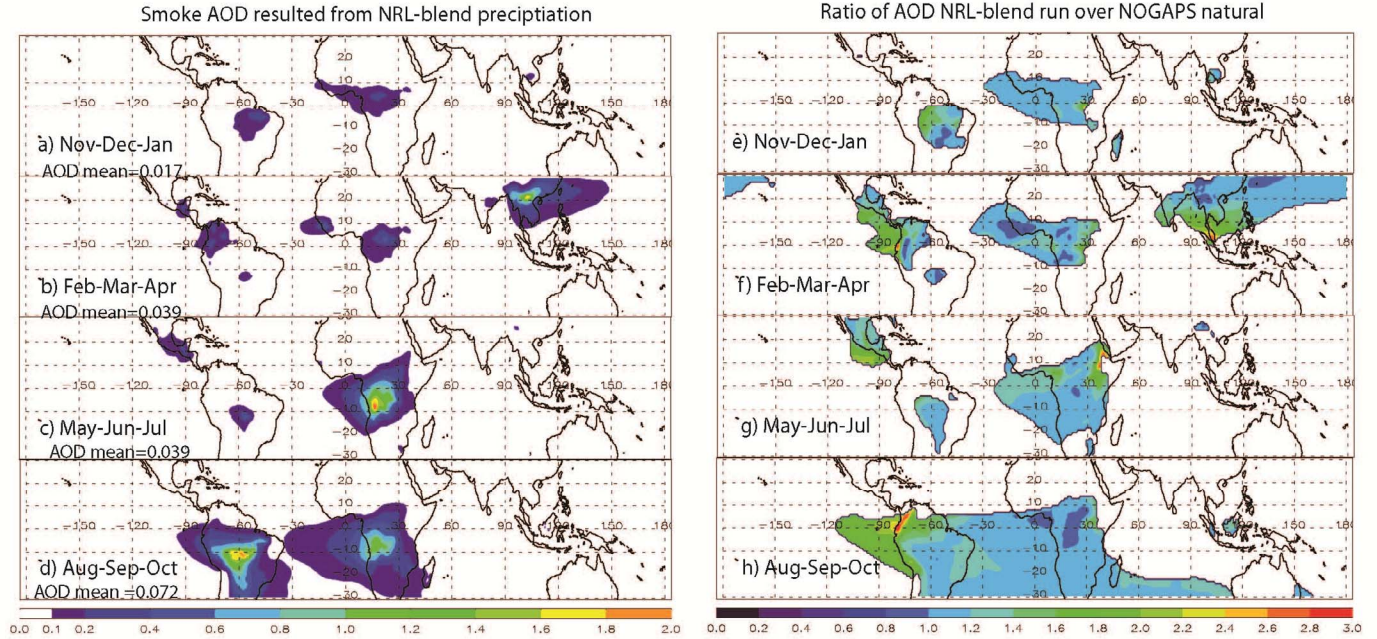


**Figure 2.**  $1^\circ$  along-track gridded CALIOP profiles for the 0304 UTC orbital pass on 20 July 2007 between  $0^\circ$  and  $40^\circ$  N from 0.0 to 10.0 km MSL of (a)  $0.532 \mu\text{m}$  attenuated backscatter ( $\text{km}^{-1} \text{sr}^{-1}$ ), (b)  $0.532 \mu\text{m}$  linear depolarization ratio, (c)  $1.064 \mu\text{m}$  attenuated backscatter ( $\text{km}^{-1} \text{sr}^{-1}$ ), (d) attenuated color ratio, (e)  $0.532 \mu\text{m}$  attenuated backscatter relative uncertainty and (f)  $1.064 \mu\text{m}$  attenuated backscatter relative uncertainty. Derived cloud boundary tops, which vary by channel, are denoted by asterisks and base heights by plus symbols.



**Figure 3.** *FLAMBE/NAAPS seasonal optical depths (550 nm) from the natural run using the baseline FLAMBE emissions product (a)–(d) and MODIS AOT data assimilation (e)–(h).*





**Figure 4. Left: Smoke AOD resulting from NRL-blend precipitation for 4 biomass burning periods in 2007. Right: Ratio of smoke AOD resulting from NRL-blend precipitation over smoke AOD resulting from NOGAPS precipitation for 4 biomass burning periods in 2007 (colored for regions with AOD > 0.05 in NRL-blend run).**